**Final Report**

# A two-way shape change polymeric laminate with fast, large and controllable deformation in response to Joule heat

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14. ABSTRACT
**In this project a polymeric laminate composite was fabricated from a carbon fiber reinforced plastic (CFRP) plate and a polyvinylchloride (PVC). The PVC-CFRP laminate worked as a bimorph actuator. Bending behavior of the PVC-CFRP laminate was tested by fully submerging the laminate in a water bath and also changing the environmental temperature. It is observed that the PVC-CFRP laminate has a number of advantages compared to other polymer-based actuators: (i) it exhibits relatively fast shape change; (ii) it generates a relatively high level of force; (iii) it is mechanically strong; (it) it requires no solvent; and (v) it exhibits two-way shape change. Moreover, the bending curvature and the blocking force of such a laminate are solely determined by the laminate temperature, which can be controlled by Joule heating. This makes PVC-CFRP laminate an electrically controllable actuator.**

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## 1. Motive

The unique properties of polymer-based actuators have drawn a great deal of attention recently. For instance, gel actuators exhibit huge strain, ionic polymer metal composite (IPMC) actuators show fast and large bending even in response to quite low voltages, and conducting polymer-based actuators demonstrate uniaxial mode strain change when a voltage is applied. However, no practical polymer-based actuators are yet available due to various drawbacks, including (i) slow shape change, (ii) low force generation, (iii) mechanical weakness, (iv) the need for a solvent and (v) one-way shape change. These drawbacks should be overcome for fabricating a practical polymer-based actuator. In this research, I attempted to fabricate a polymer-based actuator which did not have these drawbacks. Furthermore, this project tried to improve the performance of the polymer-based actuator so that it could be electrically activated.

## 2. Thermo-responsive two-way shape changeable polymeric laminate

In this project a polymeric laminate composite was fabricated from a carbon fiber reinforced plastic (CFRP) plate and a polyvinylchloride (PVC). A CFRP plate (70 mm in length × 10 mm in width × 0.5 mm in thickness) and a PVC plate (70 mm in length × 10 mm in width × 0.4 mm in thickness) underwent preheat treatment first by the following method. A CFRP and a PVC plates were submerged into a 340 K hot water for more than an hour and the hot water was allowed to cool down naturally to 300 K. The preheat treatment eliminated residual stress and residual strain from the CFRP and PVC plates. The CFRP and PVC plates were glued with adhesive of CC-33A (Kyowa Electronic Instruments Co., Ltd, Tokyo) each other, where the adhesive layer thickness was 0.1 mm. Hereafter the laminate is called PVC-CFRP laminate and its structure is shown in Fig. 1.

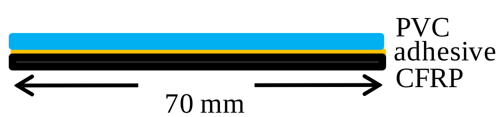
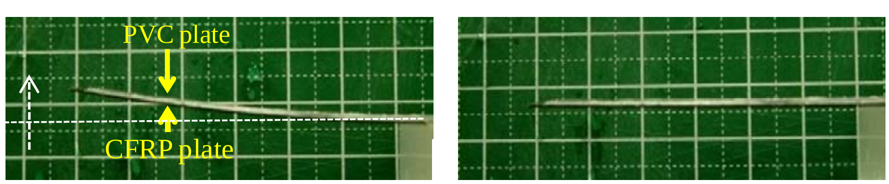



Figure 1 Structure of PVC-CFRP laminate

The resulting PVC-CFRP laminate underwent another heat treatment. The PVC-CFRP laminate was submerged into a 340 K hot water and a 300 K water alternately. Although the PVC-CFRP laminate initially took a straight shape in 300 K water and a deflected shape in a 340 K hot water, it came to take a deflected shape in 300 K water and a straight shape in 340 K hot water, and this shape change behavior in response to environmental temperature never changed after this heat treatment. The PVC-CFRP laminate worked as a bimorph actuator. Figure 2 shows the side view of PVC-CFRP laminate (a) in deflected state at 300 K and (b) in straightened state at 340 K.




(a) (b)

Figure 2 Side views of PVC-CFRP laminate at (a) 300 K and (b) 340 K

Right end of the PVC-CFRP laminate is horizontally fixed.

Bending behavior of the PVC-CFRP laminate was tested by fully submerging the laminate in a water bath. Fig. 3 shows PVC-CFRP bending curvature vs. bath temperature, where the bath temperature was raised up to 340 K and cooled to 295 K repeatedly. It clearly shows that the bath temperature determines the bending curvature uniquely. Hence, its bending is well-controllable by the control of environmental temperature. At the same time, it was observed that the PVC-CFRP laminate could generate relatively high force.

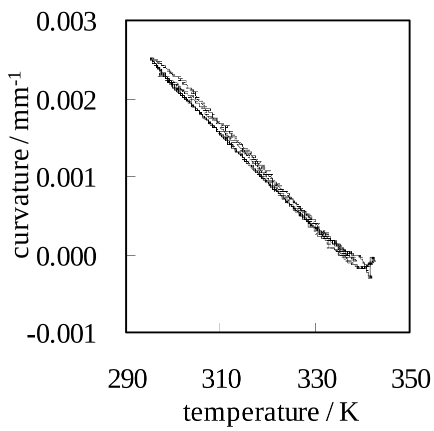



Figure 3 PVC-CFRP bending curvature vs. bath temperature

Fig. 4 shows that deflection of PVC-CFRP laminate caused by environmental temperature control under a 28 g load of coins. Unlike other types of polymeric actuator, the PVC-CFRP laminate bending is well-controllable by the environmental temperature control and can generate relatively high force.


(a) (b) (c)

Figure 4 Deflection of PVC-CFRP laminate in thermal cycling under a load (28g of coins)
(a) at 300 K before heating (b) at 340 K (c) at 300 K after cooling

The PVC-CFRP laminate exhibits relatively fast two-way shape change and generated relatively high force. Furthermore, it is perfectly in the solid state and relatively mechanically strong especially owing to the CFRP plate. Therefore, the CFRP-PVC laminate overcomes all the drawbacks of (i) to (v). Hence, CFRP-PVC laminate is a quite promising thermo-responsive actuator for its practical use.

**3. Electroactive thermo-responsive two-way shape changeable polymeric laminate**

PVC-CFRP laminate shape can be varied by controlling environmental temperature. Fast shape change is achievable by using a water bath. Shape change of PVC-CFRP laminate is immediately induced by submerging it into the water bath. Use of a water bath for controlling environmental temperature is quite effective way of fast shape change but the use of water bath is a quite impractical way of operating the PVC-CFRP laminate shape. The most convenient and practical way of deformation control is electrical control. A component of the PVC-CFRP laminate is a CFRP plate, and it contains carbon fibers. The carbon fibers could generate some heat under applied voltage. Therefore, merely imposing a voltage on the CFRP plate could cause deformation of PVC-CFRP laminate. Now experimentally verified if such an electrically-driven PVC-CFRP laminate could be fabricated.

Another PVC-CFRP laminate was fabricated by gluing a CFRP plate basically by the same procedure described in the section 2 except that the CFRP length was 2 cm longer than that used for the PVC-CFRP laminate fabricated in the section 2. The structure of newly fabricated PVC-CFRP laminate is shown in Fig. 5. The PVC-CFRP laminate underwent further treatment: Edges of the CFRP plate of the PVC-CFRP laminate were shaved and electrically conductive paste was painted on those edges. Those edges served as electrodes.

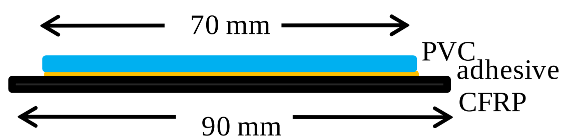



Figure 5 Structure of PVC-CFRP laminate

The resulting PVC-CFRP laminate underwent heat treatment: The PVC-CFRP laminate was submerged into a 340 K hot water and a 300 K water alternately, and it came to take a deflected shape in 300 K water and a straight shape in 340 K hot water.

3.1 Bending curvature and surface temperature

Bending of the PVC-CFRP laminate was tested by imposing a constant voltage on the CFRP plate of the PVC-CFRP laminate.

The right-hand end of the laminate was clamped horizontally in a jack as shown in Fig. 6, and both edges of the CFRP layer were connected to a power supply. The left-hand end of the laminate was virtually free, as a light, deformable electric wire was used to make the power connection there. The PVC-CFRP laminate was in deflected state, because of residual stress brought about in the specimen processing stage. During the bending tests, the precision balance shown in Fig. 6 was removed. Constant voltages (3.5, 4.5 and 5.5 V) were imposed on the CFRP layer intermittently. The PVC-CFRP laminate exhibited shape change due to Joule heating when a voltage was applied, but tended to return to its initial shape, when the voltage was removed because the laminate cooled due to natural convection. The vertical displacement and surface temperature of the laminate were measured with a laser displacement sensor and radiation thermometers, respectively, as a function of time, and the vertical displacement was later converted into bending curvature values for more common understanding of PVC-CFRP laminate shape change. The current flowing through the CFRP layer was measured, using a shunt resister (see Fig. 6).

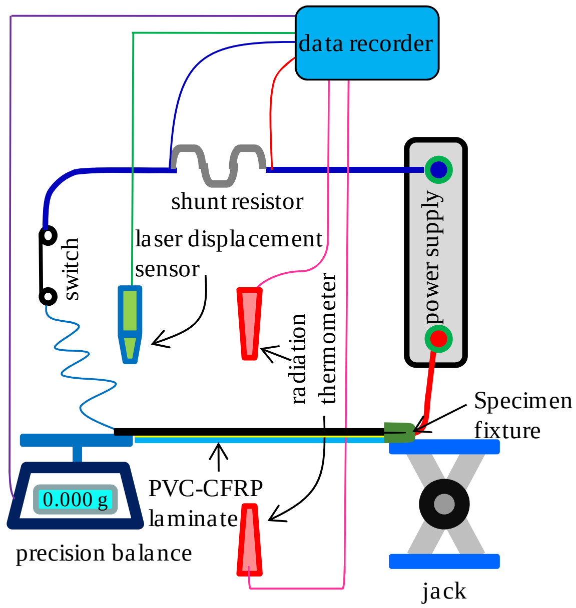



Figure 6 Experimental setup for bending testing and blocking force measurement

A PVC-CFRP laminate is horizontally clamped and the PVC layer faces down.

Figure 7 illustrates the results of the bending tests. It shows the surface temperature and current flow through the CFRP layer over time for the three different voltages (3.5, 4.5 and 5.5 V). The initial surface temperature of the CFRP layer was 293 K (i.e., room temperature). A constant voltage was applied and was removed when the surface temperature of the CFRP layer reached 333 K. When the surface temperature dropped back to 293 K, the voltage was reapplied and the cycle was repeated. The current always followed the voltage immediately with no lag. The diagrams in Fig. 7 show the surface temperature of the CFRP layer and the PVC layer. However, because the values for both were virtually identical, only one trace is apparent. It is therefore strongly speculated that that PVC-CFRP laminate is homogeneously heated electrically as it is heated in a water bath. The surface temperature of the PVC and CFRP represent the temperature of entire body of the PVC-CFRP laminate. Hence, the PVC-CFRP bending curvature may be determined solely by the CFRP (or PVC) surface temperature, as per the results obtained for the bending behavior of PVC-CFRP laminate using a water bath for temperature control.

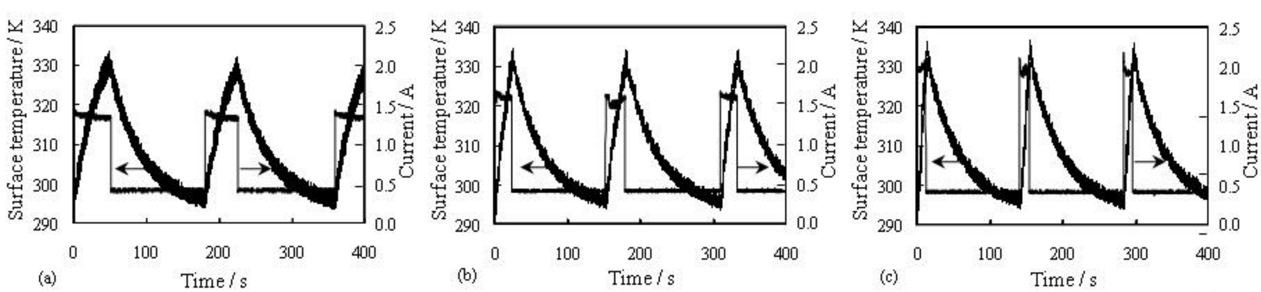



Fig. 7. Surface temperature and current of PVC-CFRP laminate under an intermittently imposed constant voltage: (a) 3.5 V; (b) 4.5 V; (c) 5.5 V

Figure 8 (a) shows the bending curvature of the PVC-CFRP laminate during the bending tests of Fig. 7. Fig. 8 (b) shows the bending curvature with respect to the surface temperature of the CFRP layer, where $C_{3.5}$, $C_{4.5}$ and $C_{5.5}$ represent the bending curvature of the PVC-CFRP laminate when voltages of 3.5, 4.5 and 5.5 V were respectively applied to the laminate intermittently and $T_{3.5}{}^{C}$, $T_{4.5}{}^{C}$ and $T_{5.5}{}^{C}$ represent the surface temperature of the CFRP layer when these voltages were applied in the same way. All the curves shown in Fig. 8 (b) fall on the almost same straight line, and offsetting has been added in the graphs to separate the three curves. Hysteresis was not significant. The data curves in Fig. 8 show that bending curvature was dependent on the surface temperature of the CFRP (or PVC) layer regardless of the voltage applied. The rate of bending, however, increased with voltage, since the current (i.e., the source of Joule heat) depended on the voltage as shown in Fig. 7.

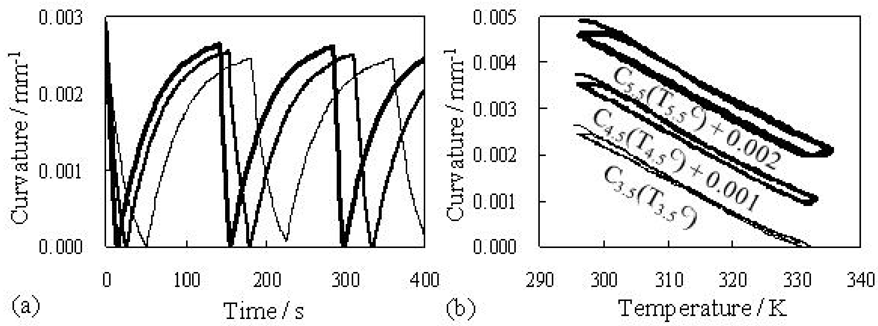



Fig. 8. (a) PVC-CFRP laminate bending curvature over time for three values of applied voltage: fine curve, 3.5 V; medium curve, 4.5 V; thick curve, 5.5 V. (b) PVC-CFRP laminate bending curvature versus CFRP surface temperature for the same three voltages. Since all curves fall in the same place, offsets have been added to separate them for clarity.

## 3.2 Force generation

The setup illustrated in Fig. 6 was again used for blocking force measurements, and the laser displacement sensor was removed. The laminate was first straightened by applying a voltage of 4.5 V, its left-hand end was placed on the platform of the precision balance, and the voltage was turned off. The laminate started to curve downward due to natural convection cooling, thereby pushing down the platform of the precision balance, which in turn detected the blocking force.

Figure 9 shows the results of the blocking force tests. It can be seen that the PVC-CFRP laminate was not only mechanically strong but also generated a relatively high force for a polymer-based actuator. Figure 9 (a) shows the blocking force and surface temperature of the CFRP layer over time while the laminate was heated and cooled repeatedly. As seen in the bending tests described previously, the surface temperature was basically the same as that of the entire laminate. The blocking force reached a maximum of over 200 mN. Figure 9 (b) relates the blocking force to the surface temperature of the CFRP layer. Again, it can be seen that there is very little hysteresis and that the force is completely determined by the CFRP (or PVC) surface temperature.

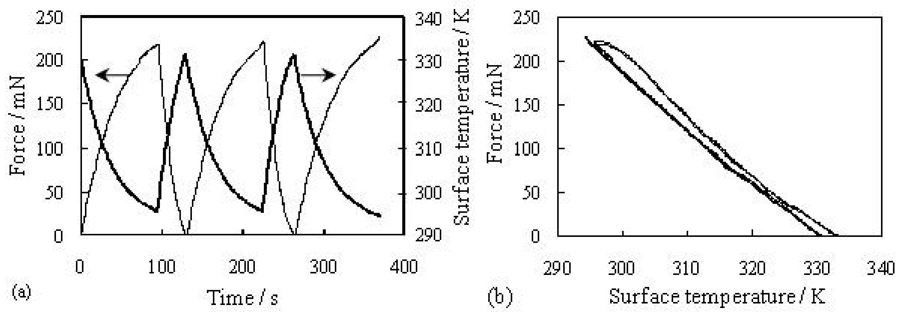



Fig. 9. (a) PVC-CFRP laminate blocking force and CFRP surface temperature over time
(b) Blocking force versus surface temperature for the PVC-CFRP laminate

## 4. Conclusion

In summary, PVC-CFRP laminate has a number of advantages compared to other polymer-based actuators: (i) it exhibits relatively fast shape change; (ii) it generates a relatively high level of force; (iii) it is mechanically strong; (it) it requires no solvent; and (v) it exhibits two-way shape change. Moreover, the bending curvature and the blocking force of such laminate are solely determined by the laminate temperature, which can be controlled by Joule heating. This makes PVC-CFRP laminate an electrically controllable actuator.

**Published papers (refereed)**

1 H. Tamagawa, W. Lin, M. Sasaki, “ELECTRICAL ACTIVATION OF THERMO-RESPONSIVE PVC-CFRP LAMINATE ACTUATORS” accepted in Functional Materials Letters, 2011.

**Conference papers (refereed)**

1 W. Lin, M. Sasaki, H. Tamagawa, “Symmetric deflection of CFRP-based polymeric laminate”, submitted for 2011 ICMIT, Shenyang China, (2011).

**Related accomplishments published under the financial support of AOARD in 2009 (one year earlier financial support )**

1 H. Tamagawa, “Thermo-responsive two-way shape changeable polymeric laminate”, Materials Letters, Volume 64, Issue 6, 31 March 2010, Pages 749-751.

2 H Tamagawa, K. Kikuchi, G. Nagai, “Mechanical characteristics of a thermo-responsive two-way shape change polymeric laminate”, Sensors and Actuators A: Physical, Volume 163, Issue 1, September, 2010, Pages 356-362.